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Coastal and Hydraulics Laboratory

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Numerical Model Investigation

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Preface

This report presents the results of a numerical model investigation used to predict average salinity changes that will occur in the Lake Pontchartrain Basin as a result of varying levels of closure of the Mississippi River-Gulf Outlet below Lake Borgne, LA.

This investigation was conducted from January 2000 through August 2000 at the U.S. Army Engineer Research and Development Center (ERDC), Vicksburg, MS, by Dr. R. C. Berger, Mr. A. R. Carrillo, and Ms. M. S. Sarruff of the Coastal and Hydraulics Laboratory (CHL), and Mr. B. J. Thibodeaux of the U.S. Army Engineer District, New Orleans (LMN). Funding was provided by the New Orleans District.

The work was performed under the general direction of Mr. Thomas W. Richardson, Acting Director, CHL, and Dr. R. T. McAdory, Chief, Tidal Hydraulics Branch.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and COL John W. Morris III, EN, was Commander.

Conversion Factors, Non-SI Units of Measurement to SI Units

Multiply	By	To Obtain
Cubic feet	0.02831685	Cubic meters
Feet	0.3048	Meters
Square feet	0.09290304	Square meters

1 Introduction

Background

The Mississippi River-Gulf Outlet (MRGO) consists of a ship channel 36 feet deep and 500 feet wide, extending approximately 76 miles from the junction of the Inner Harbor Navigation Canal and the Gulf Intracoastal Waterway in New Orleans, LA, to the -38 mlw (mean low water) foot contour in the Gulf of Mexico. The purpose of the MRGO is to provide a deep draft channel to the Port of New Orleans Inner Harbor facilities.

Since the MRGO's completion in January 1968, saltwater flux from the MRGO through direct connections to Lake Borgne and the Gulf Intracoastal Waterway has contributed to an increase in the salinity concentration of the lakes and Biloxi Marshes. Attempts by the U.S. Army Engineer District, New Orleans (LMN) to mitigate this salinity increase through the operation and maintenance program have met with little or no success.

Therefore, the New Orleans District is participating in an Environmental Protection Agency sponsored study, "Mississippi River - Gulf Outlet, LA, Re-evaluation Study," focusing on the deep draft navigation, environmental, and flood control aspects of the project and the need for continued maintenance. The purpose of the re-evaluation study is to determine if the existing channel should be modified and to provide the advisability of continuing its operation. In support of the effort, the U.S. Army Engineer Research and Development Center, Waterways Experiment Station (ERDC-WES) Coastal Hydraulics Laboratory (CHL) was tasked to model several plans for partial blockage of the MRGO south of Lake Borgne, LA.

Objective

The objective of the work presented herein is to predict the average salinity changes that will occur in the Mississippi and Louisiana estuaries of the Lake Pontchartrain Basin (Figure 1), particularly that part known as the Biloxi Marshes, resulting from partial closure of the MRGO below Lake Borgne.

The purpose of this report is to present the results of a numerical model investigation addressing this objective. The modeled region includes Lake

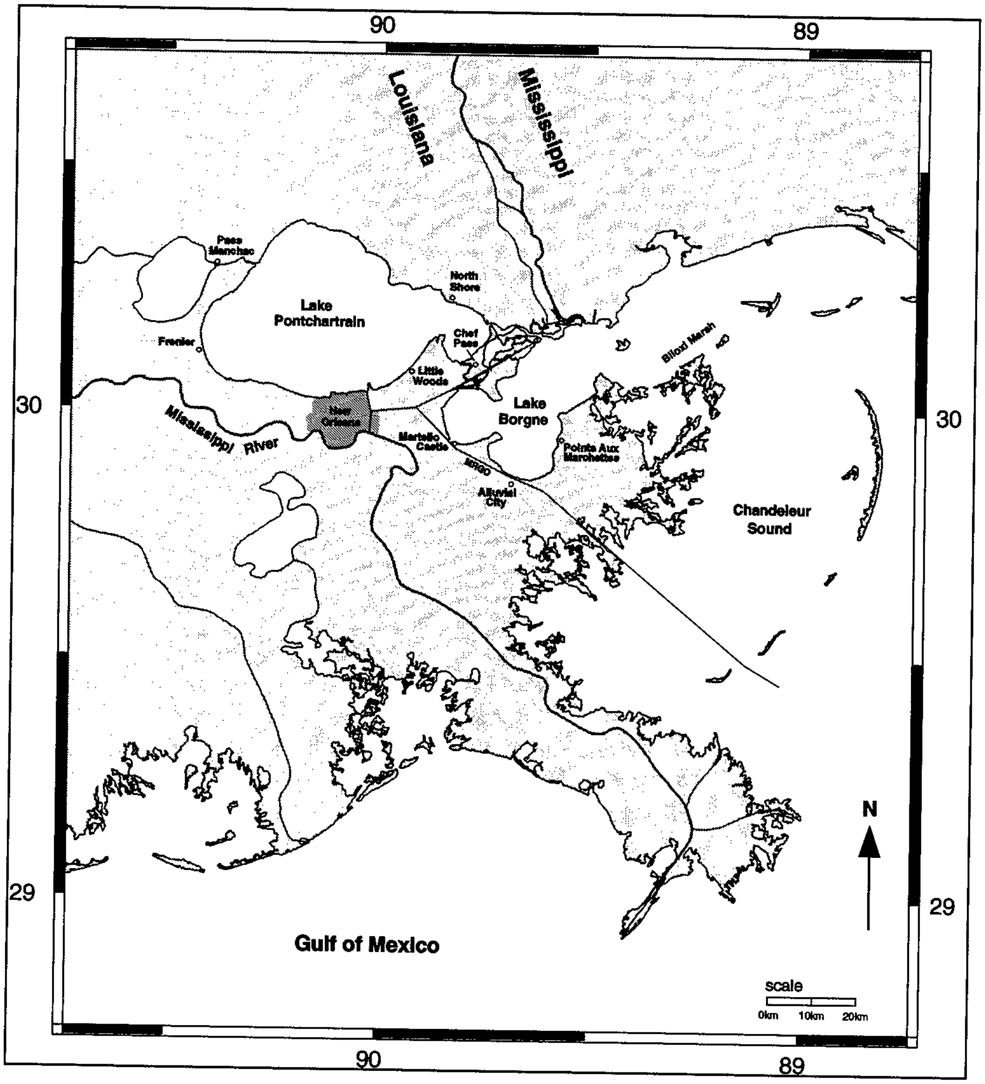

Figure 1. Vicinity map

Pontchartrain, Lake Borgne, the MRGO, the Inner Harbor Navigation Channel (IHNC), the Gulf Intracoastal Waterway (GIWW), the Rigolets, the Chef Menteur, segments of Mississippi Sound, Chandeleur Sound, Breton Sound, and at least a portion of the Biloxi Marshes, as shown in Figure 1.

Based on the results of the initial study, additional investigation was requested to evaluate the length of time necessary for the system's salinity to return to normal observed levels after an unusual weather event. In this case, the surge from Hurricane Juan is used to constitute this event. The results from this additional investigation can be found in Appendix B.

2 Lake Pontchartrain Basin

The Lake Pontchartrain Basin consists of Lake Maurepas, Lake Pontchartrain, Lake Borgne, the Biloxi Marshes, and Chandeleur Sound, plus associated marshlands and waterways. The Basin is described in detail by the New Orleans District (USAED, New Orleans, 1984, 1990), Pankow et al. (1989), and the U.S. Army Corps of Engineers Committee on Tidal Hydraulics (CTH) (1995). A summary of pertinent factors will be provided here.

Hydrology

The largest tributary to the area is the Pearl River with a mean annual flow of about 10,000 cfs. The Pearl River discharges into Lake Borgne near the mouth of the Rigolets, one of three tidal waterways out of Lake Pontchartrain. Several smaller rivers, the largest of which are the Amite, Tickfaw, Tangipahoa, and Tchefuncta Rivers, flow into Lake Pontchartrain and Lake Maurepas. The annual freshwater flow into Lake Pontchartrain averages about 3,800 cfs.

Hydrodynamics

Tides in the basin are principally diurnal, with mean ranges of 0.3 ft (Lake Maurepas) to 0.5 ft (Lake Pontchartrain) to 1.4 ft (Chandeleur Sound). Sustained winds can raise or lower peak astronomical tide levels by several feet for short periods. Mean water levels are affected by winds, freshwater runoff, and seasonal trends in the Gulf of Mexico.

Figure 2 illustrates typical seasonal variability in mean water level. It displays monthly mean water levels for 1940-1950 at Eugene Island at the Gulf entrance to Atchafalaya Bay (USAED, New Orleans, 1982) which are representative of Gulf levels throughout the area in that mean water levels are lower in winter and midsummer and higher in spring and fall.

Currents and circulation are controlled by tides, winds, freshwater discharges, and gulf currents. Flows in the MRGO are also affected to some extent by density currents (Donnell and Letter 1991).

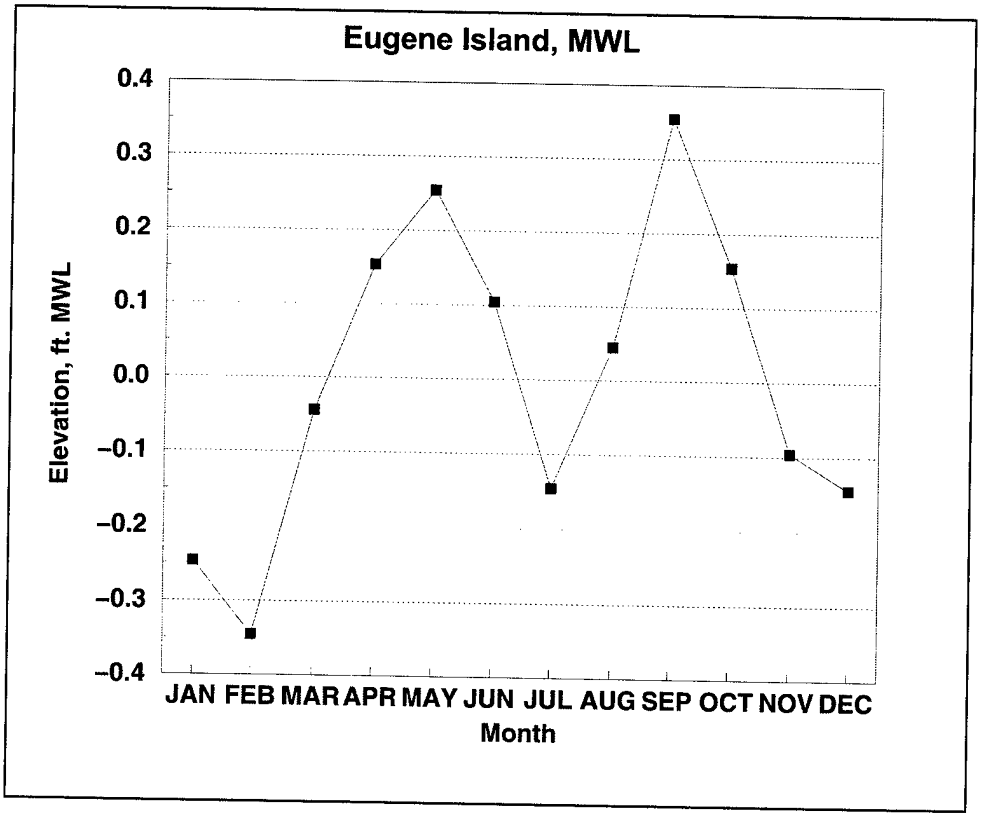

Figure 2. Intra-annual mean water level variation at Eugene Island, 1940-50

Lake Pontchartrain Historical Salinity

Historical salinity data for five stations in the Pontchartrain Basin were analyzed. These stations are Pass Manchac near Pontchatoula, Lake Pontchartrain at Little Woods, Chef Pass near Lake Borgne, Lake Pontchartrain at North Shore and Bayou LaLoutre at Alluvial City. The data are evaluated as pre- and post-MRGO periods to identify changes to the salinity regime due to the MRGO. The bulk of the project was completed in July 1963, but a plug at Paris Road was not removed until 1968. Nevertheless, the condition between 1963 and 1968 did allow intrusion up the MRGO to Lake Borgne.

The data indicate that the lowest salinities are generally in the late spring and highest in the summer and late fall. This reflects seasonal variations in freshwater inflows from the major rivers and streams in the basin. The salinities of Lake Borgne and Lake Pontchartrain normally range from fresh to brackish. During periods of extreme low flows, Lake Maurepas can become brackish.

Salinities in Lake Borgne generally range from 2 to 15 ppt and are strongly influenced by Pearl River discharges and inflow from the Rigolets and Chef Pass. Higher salinity water from the MRGO enters Lake Borgne through breaks in the marshes between the two water bodies.

Analyses of salinity data indicate that the most notable increase in monthly average salinity occurred after 1963. Mean monthly salinity increased for all months for the period subsequent to 1963. This increase can be attributed partly to the partial completion of the MRGO in 1963 which provided a major access for saline water to enter Lake Maurepas, Lake Pontchartrain, and Lake Borgne.

Monthly summaries of salinity for pre- and post-MRGO indicate that salinity has increased on the average by the following amounts:

a. 1.3 ppt at Lake Pontchartrain, North Shore.

b. 1.8 ppt at Lake Pontchartrain, Little Woods.

c. 0.4 ppt at Pass Manchac near Pontchatoula.

d. 2.4 ppt at Chef Pass near Lake Borgne.

e. 4.3 ppt at Bayou LaLoutre, Alluvial City.

The salinity regime in the area has stabilized and no significant increase in average annual salinity is projected in the foreseeable future for Lake Maurepas and Lake Pontchartrain. Salinity is expected to increase in the Lake Borgne area and surrounding marshes due to land loss in the area.

Table 1 shows mean monthly pre- and post-MRGO salinity for the period 1951 to 1963 and 1963 to 1977.

Table 1
Pre- and Post-MRGO Salinity ppt

Month	Pass Manchac		North Shore		Little Woods		Chef Pass		Alluvial City	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
January	1.1	1.5	3.0	4.0	3.8	5.0	3.8	5.7	6.8	9.8
February	1.0	1.5	2.5	3.0	3.0	6.5	2.9	4.8	6.4	9.7
March	1.0	1.2	1.9	2.6	2.3	4.4	2.2	4.3	6.3	10.4
April	0.8	1.3	1.9	2.6	2.4	4.0	2.2	4.0	7.0	10.0
May	1.0	1.1	2.4	2.7	2.2	3.8	2.6	4.0	9.5	10.2
June	1.0	1.5	3.6	3.0	2.2	3.8	3.3	4.2	9.0	12.3
July	1.0	1.6	3.0	4.6	2.1	4.4	3.2	6.3	7.9	16.0
August	1.2	1.7	4.6	5.6	2.5	4.8	4.8	7.5	8.6	16.1
September	1.7	2.0	5.4	7.5	4.5	6.2	6.0	8.5	8.2	12.9
October	1.8	2.2	4.7	7.3	4.9	6.8	5.2	8.4	7.6	13.8
November	1.8	2.1	4.6	6.7	4.8	6.8	5.2	8.0	8.0	13.1
December	1.2	1.8	4.5	5.4	4.7	6.2	4.2	7.0	8.0	12.5

3 Approach

Numerical Model

TABS-MDS, the numerical model used for this investigation, is a three-dimensional finite element code originally developed by Dr. Ian King of Resource Management Associates, and modified at ERDC. It models three-dimensional hydrodynamics and salt transport accounting for unsteady river inflows, tides, wind effects, and density-driven circulation. It has been widely used by ERDC to model three-dimensional hydrodynamics and salinity at numerous locations, including Galveston Bay, TX (Berger et al. 1995). The model is described more fully in Appendix A.

Computational Mesh

Figure 3 illustrates the planform view of the computational mesh used. The mesh is three-dimensional everywhere except near the gulfward boundary and in Lake Maurepas. The 3-D grid contains 16,932 nodes and 6,701 elements distributed horizontally and vertically. The grid is refined along the MRGO, and its connections to the Gulf of Mexico, Lake Borgne, and Lake Pontchartrain. The computational mesh provides direct connections between MRGO and Lake Borgne at Shell Beach and Martello Castle. Another connection exists between Lake Borgne and the GIWW near Bayou Gentilly (southeast of Chef Menteur). These connections are sized to approximate not only the connections at those locations, but also nearby smaller connections, and thus represent an aggregation of several smaller waterways.

Model Validation

Validation for the Lake Pontchartrain Basin model was performed in a prior investigation. Details of the validation can be found in McAnally and Berger (1997).

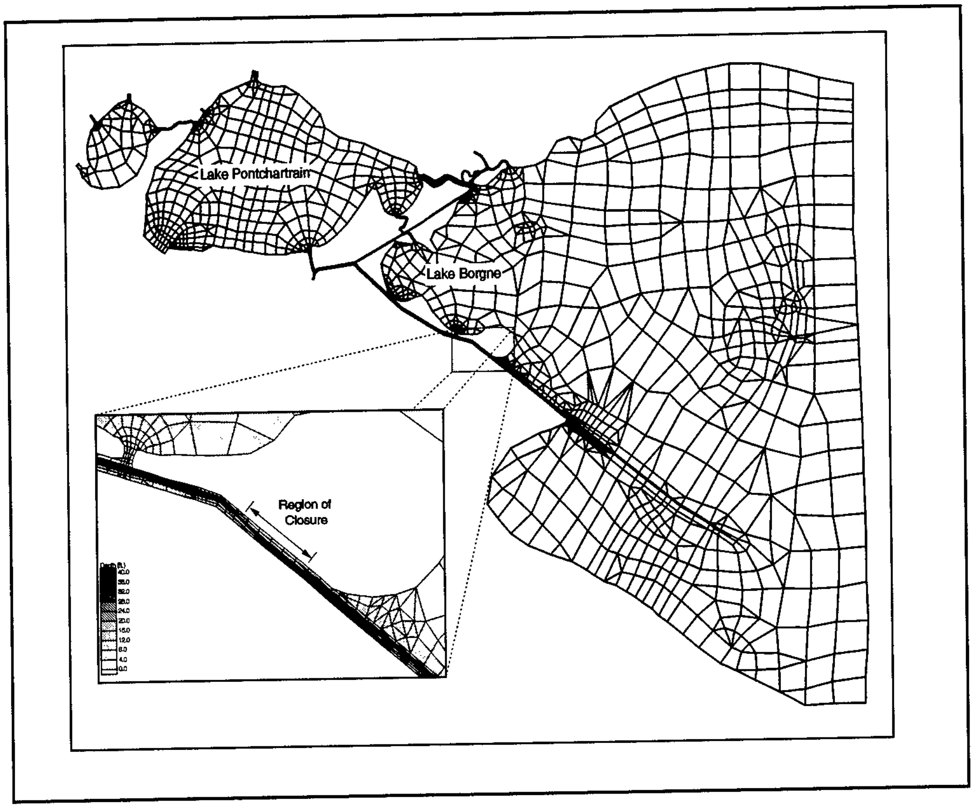

Figure 3. Computational mesh and region of closure

Experimental Conditions

Typical modeling conditions for the base and plan experiments are based on statistical measures. Since most of this work is based on prior investigations, only a brief discussion of the specifics of the experimental conditions are addressed in the following sections. For a more detailed discussion see McAnally and Berger (1997).

Boundary Conditions

Riverflows for base and plan experiments

Base and plan experiments were conducted for typical conditions, using the 50 percent exceedance flows given in Table 2. These have been corrected for ungauged areas. A complete description of the development of the flows used for the model (Table 2) is given in McAnally and Berger (1997).

Tides

Tides at the model's gulfward boundary were synthesized for the year 1982 from the tidal constituents as given by Outlaw (1982) and shown in Table 3. The

Table 2
Stream Inflow for Model Programs, cfs

Month	Pearl	Amite	Blind	Tangipahoa	Tickfaw	Tchefuncta
January	9,602	2,194	216	1,160	512	175
February	18,060	2,689	216	1,480	674	222
March	19,120	2,842	216	1,533	676	214
April	15,510	2,142	216	1,223	514	170
May	10,090	1,402	216	853	325	118
June	4,178	713	216	556	158	66
July	3,522	702	216	581	147	69
August	2,792	579	216	495	145	66
September	2,388	499	216	475	137	60
October	2,047	448	216	390	87	46
November	2,651	463	216	413	125	68
December	5,339	1,468	216	912	362	137

Table 3
Gulf Boundary Tidal Constituents

Tidal Constituents		South End of the Boundary		South of Ship Island		North End of the Boundary	
Component	Period hr	Amplitude ft	Epoch deg	Component	Period hr	Amplitude ft	Epoch deg
01	25.819	0.46	-37.4	0.51	-37.4	0.36	-50.4
K1	23.934	0.47	-38.6	0.51	-38.8	0.36	-50.2
P1	24.066	0.15	305.6	0.15	310.3	0.14	289.1
M1	24.833	0.01	323.7	0.02	328.2	0.00	329.1
J1	23.099	0.02	282.7	0.02	267.1	0.02	289.1
Q1	26.868	0.11	-40.8	0.12	-39.5	0.07	-57.5
M2	12.421	0.09	239.5	0.09	252.9	0.04	214.4
S2	12.000	0.05	264.1	0.05	284.8	0.03	235.0
N2	12.658	0.02	209.4	0.02	223.0	0.01	183.8

mean water level set to zero referred to the National Geodetic Vertical Datum (NGVD).

Wind

The wind data used were obtained from the U.S. Air Force Environmental Technical Applications Center in Asheville, NC. These data were the hourly surface winds at the New Orleans International Airport for the calendar year 1982, and were used for all base and plan experiments.

Initial Conditions

In these experiments an initial salinity field, currents, and water elevations, were obtained from previous simulations of the region (McAnally and Berger 1997), and used as initial conditions for all base and plan experiments. Since the simulations were started in January, the initial conditions had sufficient relaxation time before the first period of interest in April.

Base and Plans

The base condition (maximum depth in the MRGO cross section is 47 ft) and four levels of closure were modeled. Closure consisted of a sill across the LaLoutre Ridge in the MRGO, and the region is labeled in Figure 3. All employed the boundary and initial conditions described previously. The experiments were as follows:

a. Base: Maximum depth in the cross section is 47 ft.

b. 20-ft Plan: Closed to within a 20-ft depth.

c. 16-ft Plan: Closed to within a 16-ft depth.

d. 12-ft Plan: Closed to within a 12-ft depth.

e. Complete closure.

The numerical model calculated water-surface elevations, current velocities (three-dimensional components), and salinities at each node every 60 minutes for the 10-month period of simulation between January 1 and October 31. Those data were processed to provide average monthly salinity contour plots for base and each plan for April, May, September, and October (Plates 1-4).

4 Results and Discussion

The interest of this study is the effect of the closure of MRGO on salinities in Lake Pontchartrain, Lake Borgne, and Biloxi Marsh. The results are contained in Plates 1-4. These contain the month average isohalines for the bottom depth for each plan. The isohalines shown for each plan represent the change from the base conditions. The base conditions are the month average salinity. The plan isohalines are then changes, where a negative sign (-) indicates that the closure reduced the salinity and a positive sign (+) indicates an increase. The month averages given are for April, May, September, and October. Tables 4-7 show the values for specific station locations (approximate). The spring months are representative of the low salinity period of the year, and the autumn months indicate the maximum salinity period.

The base isohalines are found on part (a) of Plates 1, 2, 3, and 4. The spring months show salinity values in Lake Pontchartrain that are between 4 and 6 ppt. In Lake Borgne the spring month average salinity is generally shown to be between 8 and 16 ppt. The fall month-average salinity values in Lake Pontchartrain are generally between 4 and 8 ppt. In Lake Borgne in the same period, the salinity values are shown to be roughly between 12 and 20 ppt.

An obvious remark that can be made about the salinity for each plan is that the largest changes result from the complete closure. Even the 12-ft plan, which involves leaving a MRGO blockage for depths below 12 ft mean low water (mlw), is much less dramatic than the complete closure. The major result with any closure is that Lake Borgne and Lake Pontchartrain salinities decrease. There is very little change in salinity along the eastern edge of Lake Borgne. The largest salinity decreases occur along the western portion of Lake Borgne and the southeastern shore of Lake Pontchartrain. These are a result of the two major connections to MRGO from Lake Borgne and the Inner Harbor Navigation Canal that connect Lake Pontchartrain to MRGO.

The average salinity reduction for any of the partial closure plans was 0.3 ppt or less in Lake Pontchartrain and Lake Borgne. For the complete closure the spring months showed general salinity decreases compared to base of between 0 and 3.4 ppt in Lake Borgne and 0.2 to 2.4 ppt in Lake Pontchartrain. The autumn months showed general decrease of 0.2 to 3.4 ppt in Lake Borgne and between 1.0 to 3.4 in Lake Pontchartrain. The Biloxi Marsh area of eastern Lake Borgne showed very little change.

Table 4
Modeled April Monthly Average Salinity, Base Conditions and Plan Changes from Base, ppt

Location	Base	20-ft Plan	16-ft Plan	12-ft Plan	Closure Plan
Alluvial City	16.5	-0.5	-0.5	-0.6	-6.0
Chef Pass	8.4	-0.2	-0.2	-0.6	-1.7
Fenier	4.6	-0.0	-0.1	-0.1	-0.6
Little Woods	5.9	-0.2	-0.2	-0.3	-1.6
Martello Castle	15.1	-0.7	-0.7	-0.7	-6.6
North Shore	5.4	-0.1	-0.1	-0.2	-0.9
Pass Manchac	0.7	-0.0	-0.0	-0.0	-0.1
Pointe Aux Marchettes	13.9	-0.1	-0.0	0.0	-0.5

Table 5
Modeled May Monthly Average Salinity, Base Conditions and Plan Changes from Base, ppt

Location	Base	20-ft Plan	16-ft Plan	12-ft Plan	Closure Plan
Alluvial City	16.1	-0.4	-0.4	-0.5	-5.7
Chef Pass	8.9	-0.2	-0.2	-0.3	-2.2
Fenier	4.7	-0.1	-0.1	-0.1	-0.8
Little Woods	6.2	-0.3	-0.3	-0.4	-2.1
Martello Castle	15.1	-0.6	-0.7	-0.8	-6.6
North Shore	5.7	-0.2	-0.2	-0.2	-1.2
Pass Manchac	0.6	-0.0	-0.0	-0.0	-0.1
Pointe Aux Marchettes	14.3	-0.1	-0.1	-0.0	-0.8

Table 6
Modeled September Monthly Average Salinity, Base Conditions and Plan Changes from Base, ppt

Location	Base	20-ft Plan	16-ft Plan	12-ft Plan	Closure Plan
Alluvial City	17.9	-0.4	-0.4	-0.6	-5.1
Chef Pass	10.5	-0.2	-0.2	-0.2	-1.6
Fenier	4.9	-0.1	-0.2	-0.2	-1.3
Little Woods	7.1	-0.2	-0.3	-0.3	-2.3
Martello Castle	16.7	-0.4	-0.5	-0.7	-5.4
North Shore	6.9	-0.2	-0.2	-0.2	-1.3
Pass Manchac	1.0	-0.0	-0.0	-0.3	-0.3
Pointe Aux Marchettes	15.8	-0.1	-0.1	-0.0	-0.8

Table 7
Modeled October Monthly Average Salinity, Base Conditions and Plan Changes from Base, ppt

Location	Base	20-ft Plan	16-ft Plan	12-ft Plan	Closure Plan
Alluvial City	20.2	-0.5	-0.6	-0.7	-6.6
Chef Pass	11.7	-0.2	-0.2	-0.3	-1.9
Fenier	5.4	-0.2	-0.2	-0.2	-1.6
Little Woods	8.1	-0.3	-0.3	-0.4	-3.1
Martello Castle	19.3	-0.5	-0.6	-0.8	-7.2
North Shore	7.4	-0.2	-0.2	-0.2	-1.4
Pass Manchac	1.1	-0.0	-0.0	-0.1	-0.4
Pointe Aux Marchettes	17.3	-0.1	-0.1	-0.1	-1.1

It is worth noting that the change in salinity accompanying the complete closure of MRGO is similar to that expected from the historical salinity data. Table 8 shows the measured and modeled changes in salinity from pre- to post-MRGO for five stations in the Pontchartrain Basin. The measured values are based on the mean monthly salinity for the period 1951 to 1963 (pre-MRGO) and the period 1963 to 1977 (post-MRGO). The modeled values were computed using median flows rates, astronomical tides with limited tidal periods, and 1982 wind data. Given these differences, the model results are quite reasonable.

Table 8
Measured and Modeled Changes in Salinity from Pre- to Post-MRGO, ppt

Month		Pass Manchac	North Shore	Little Woods	Chef Pass	Alluvial City
April	Measured	0.5	0.7	1.6	1.8	3.0
	Modeled	0.1	0.9	1.6	1.7	6.0
May	Measured	0.1	0.3	1.6	1.4	0.7
	Modeled	0.1	0.1	2.1	2.2	5.7
September	Measured	0.3	2.1	1.7	2.5	4.7
	Modeled	0.3	1.3	2.3	1.6	5.1
October	Measured	0.4	2.6	1.9	3.2	6.2
	Modeled	0.4	1.4	3.1	1.9	6.6

5 Conclusions

This investigation is concerned with various stages of closure of the MRGO channel from the Gulf of Mexico to the city of New Orleans. Historical records indicate that when the channel was built there was an increase in salinity in Lake Pontchartrain and Lake Borgne. This model study used a sill near the connection of MRGO to the Gulf of Mexico with an elevation of -20, -16, and -12 ft mlw to provide partial closure of the channel and investigate the restoration of the historical salinity regimen. The model study also includes the base conditions of a fully open channel and complete closure of the MRGO.

The monthly average salinities from the model indicate that all of the closure plans reduced the salinity of Lake Borgne and Lake Pontchartrain. None made large changes in the salinity in the Biloxi Marshes. The change is most pronounced in Lake Pontchartrain near the Inner Harbor Navigation Canal, which is the connection to MRGO. The eastern portion of Lake Pontchartrain had a more significant reduction in salinity than did the western portion. In Lake Borgne, salinities in the areas near the connection to MRGO were most strongly reduced.

The partial closures had a very small effect. Even the MRGO closure plan that had the sill elevation of only -12 ft mlw produced reductions that were quite small compared to complete closure.

The final point is that the model results for complete closure compared to base conditions were consistent with the field historical salinity changes observed from before to after MRGO was built.

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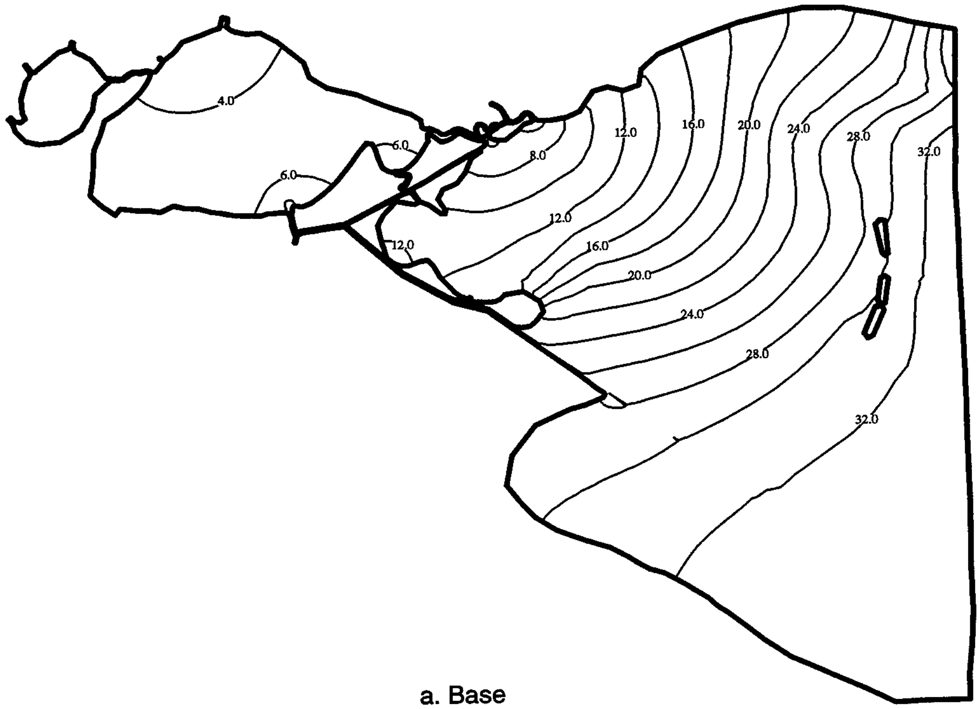

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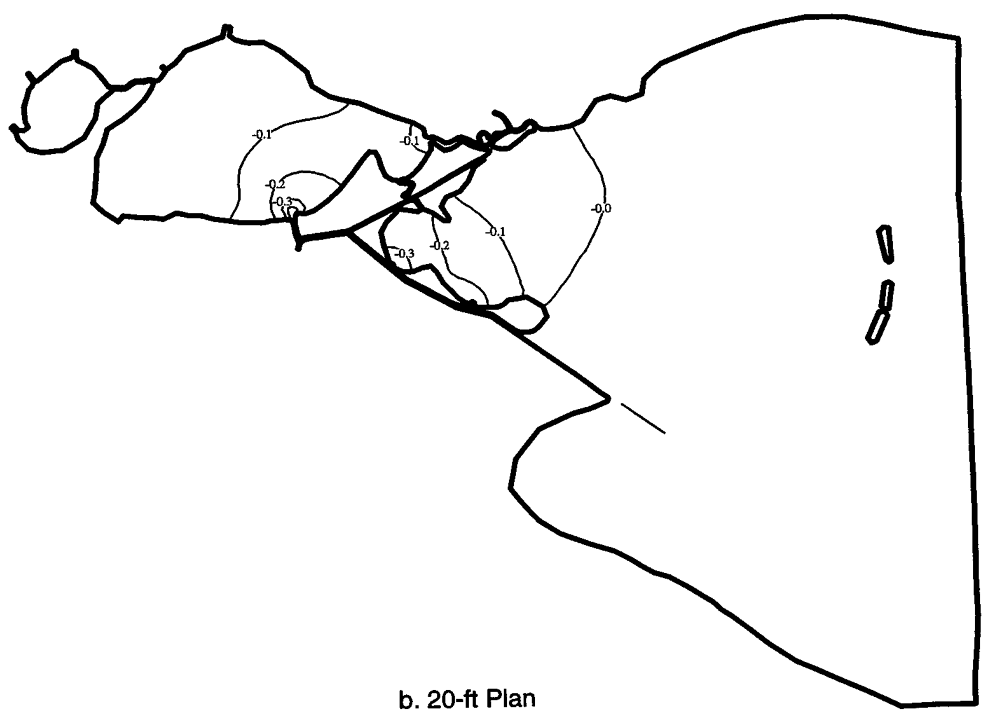
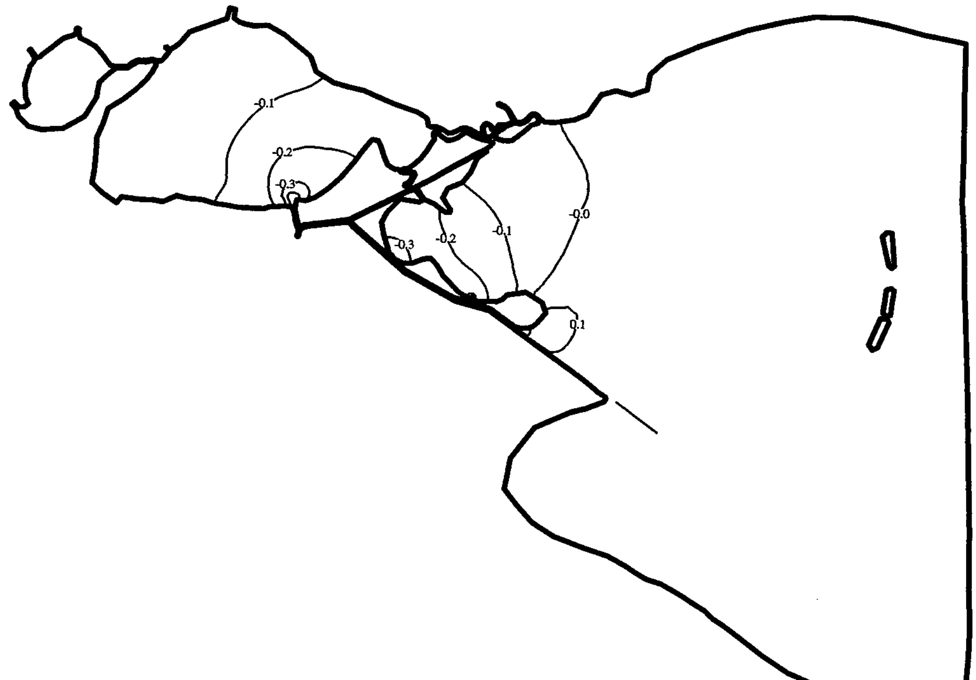


b. 20-ft Plan

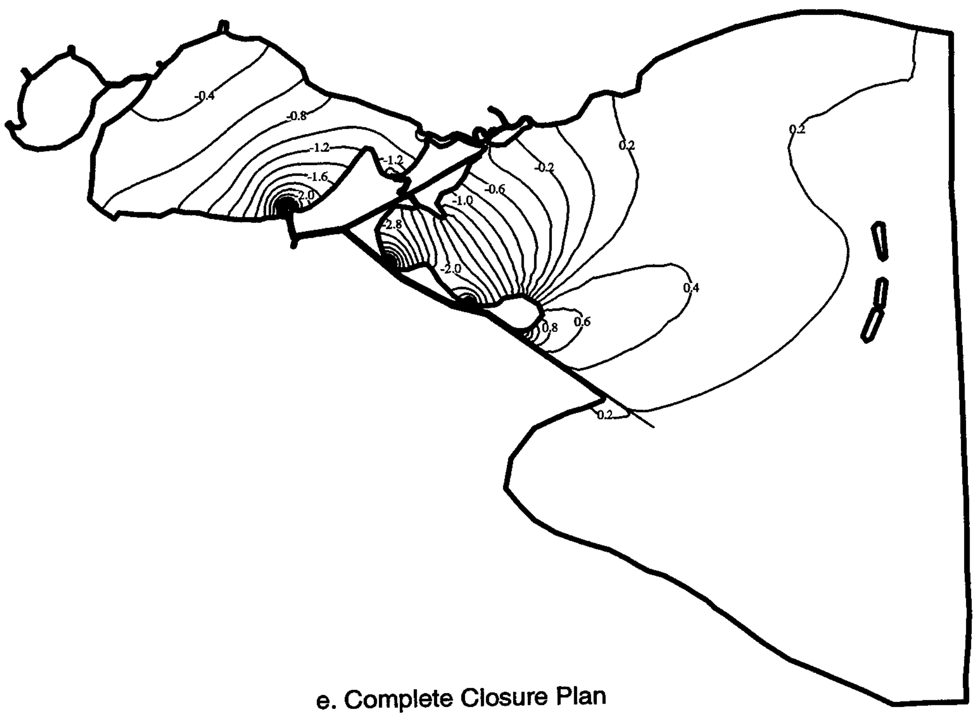
Pontchartrain Basin Isohalines
Base and Plan Changes from Base
April



c. 16-ft Plan

d. 12-ft Plan

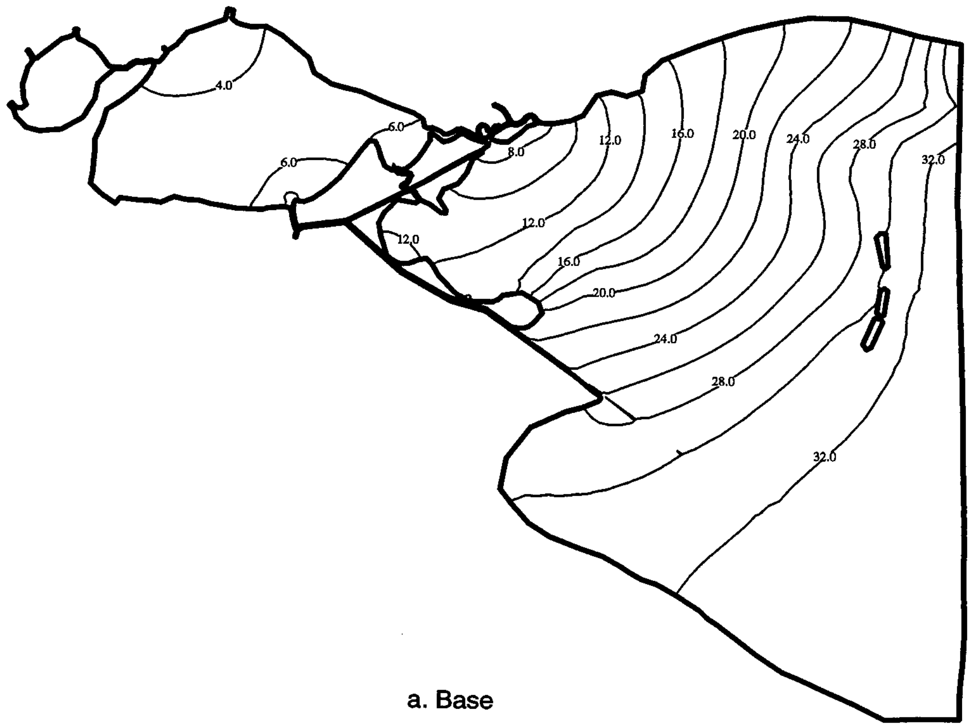
Pontchartrain Basin Isohalines
Base and Plan Changes from Base
April



e. Complete Closure Plan

Pontchartrain Basin Isohalines
Base and Plan Changes from Base
April

Plate 1
(Sheet 3 of 3)



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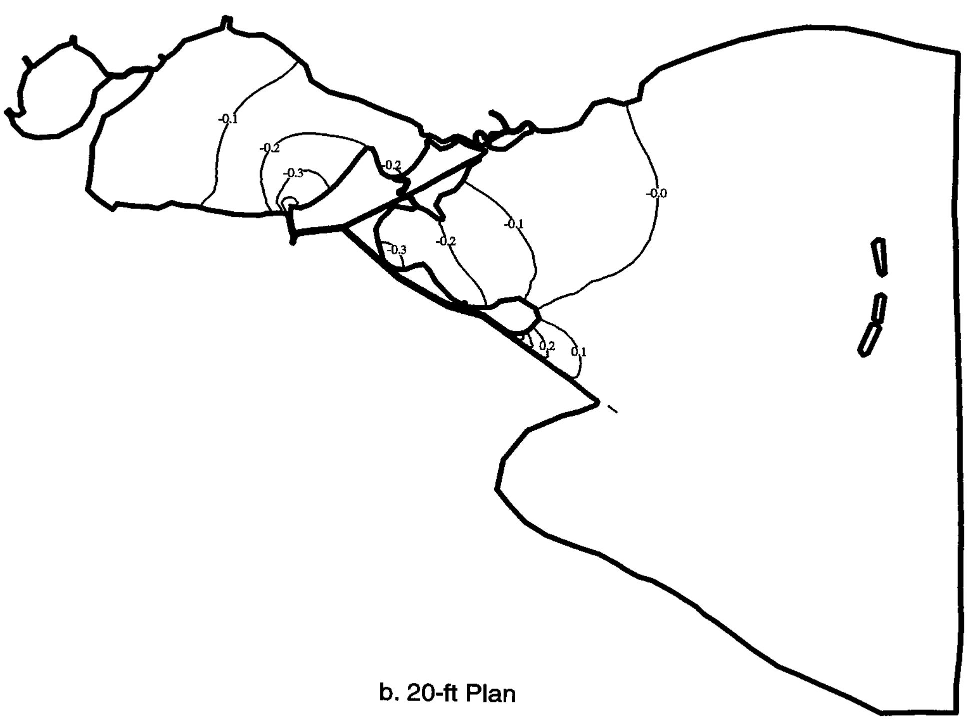
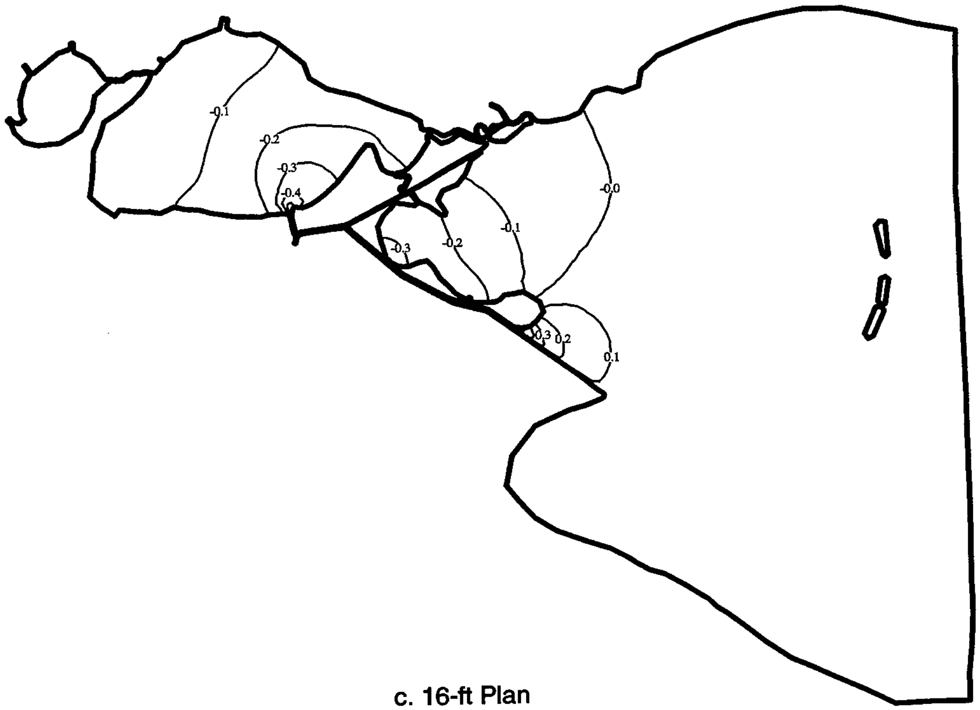


b. 20-ft Plan

Pontchartrain Basin Isohalines
Base and Plan Changes from Base
May



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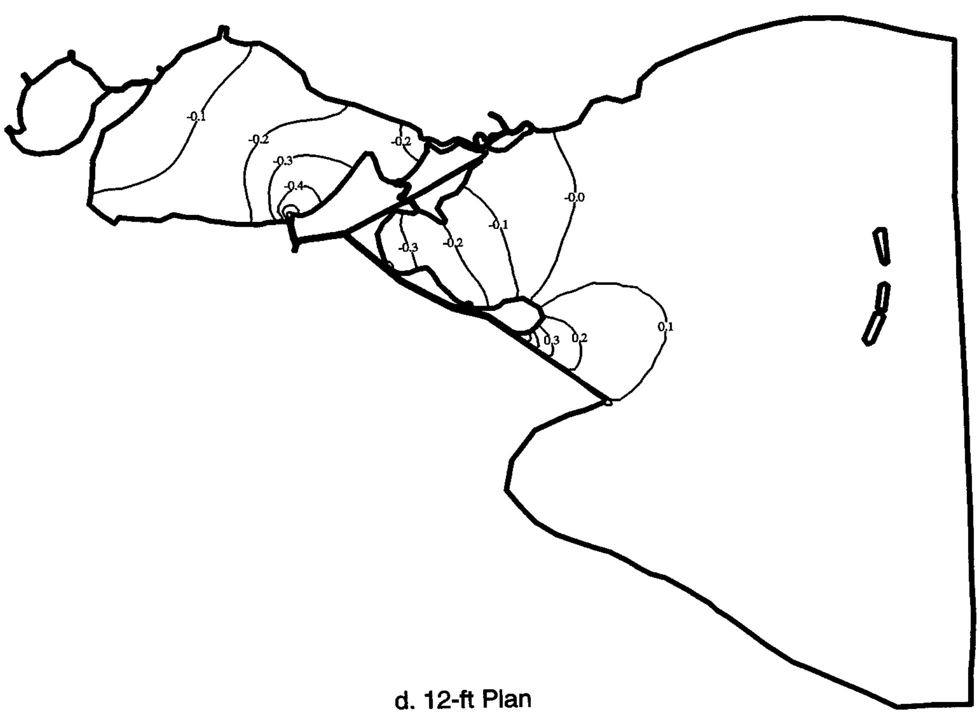

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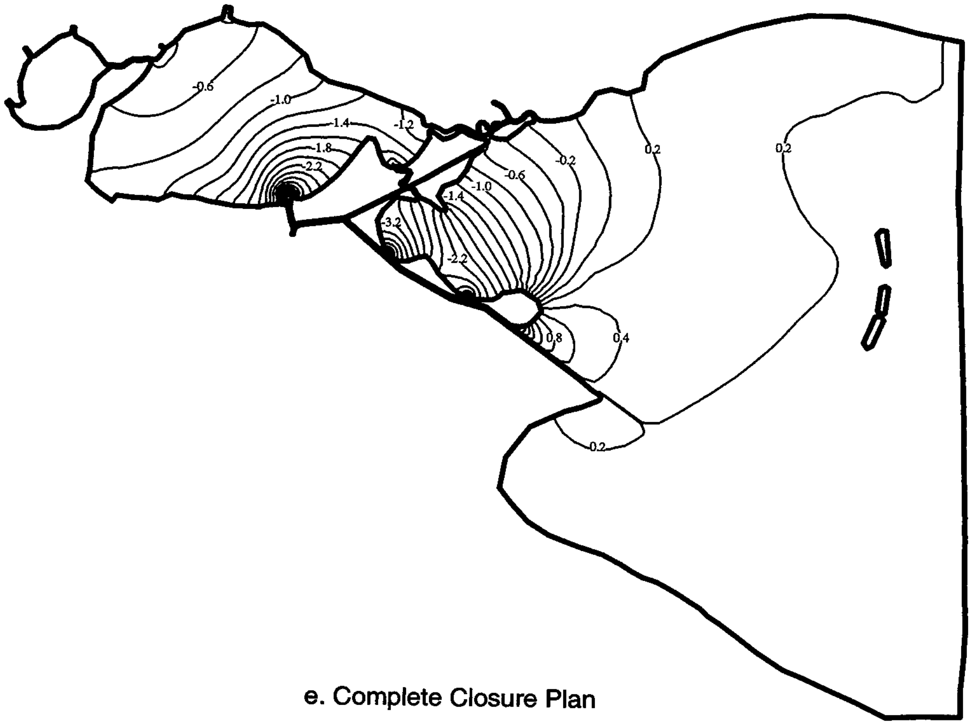
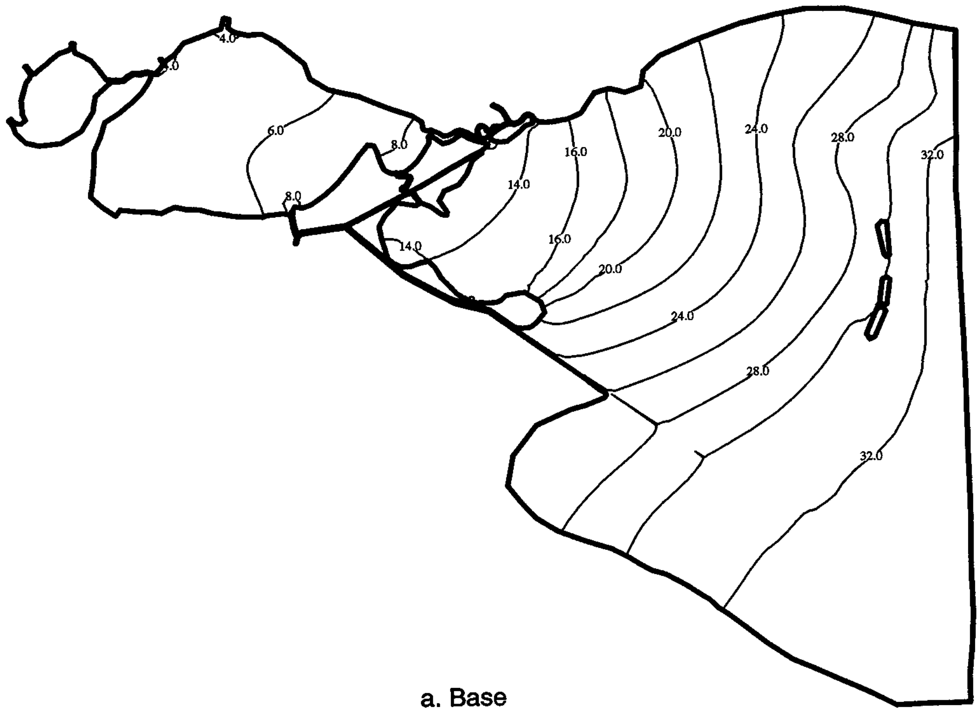
Pontchartrain Basin Isohalines
Base and Plan Changes from Base
May



e. Complete Closure Plan

Pontchartrain Basin Isohalines
Base and Plan Changes from Base
May

Plate 2
(Sheet 3 of 3)



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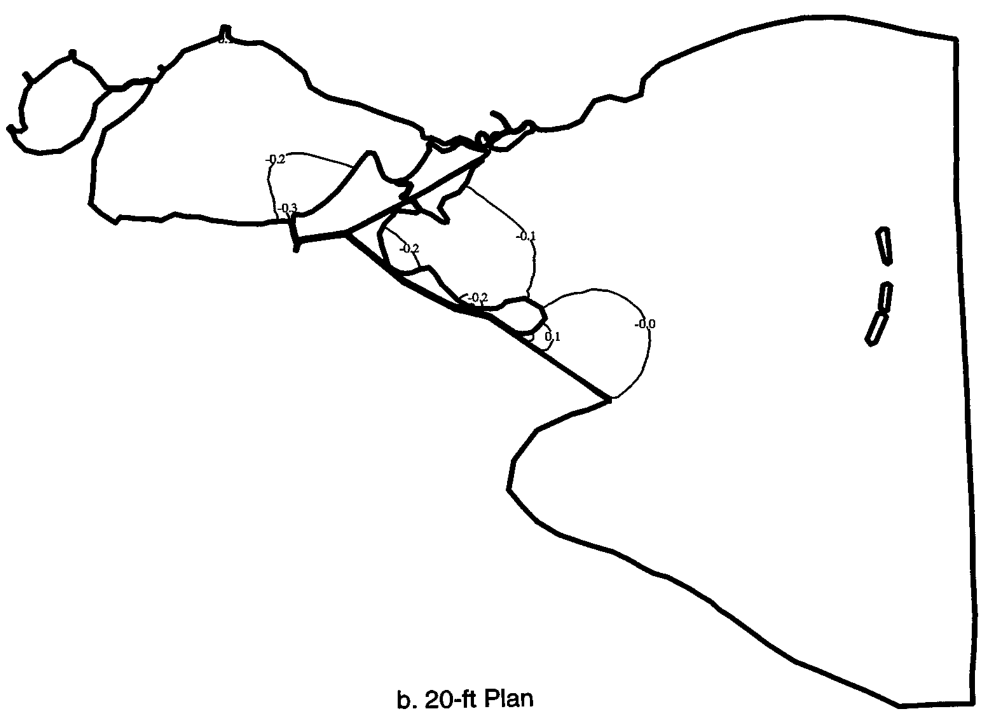
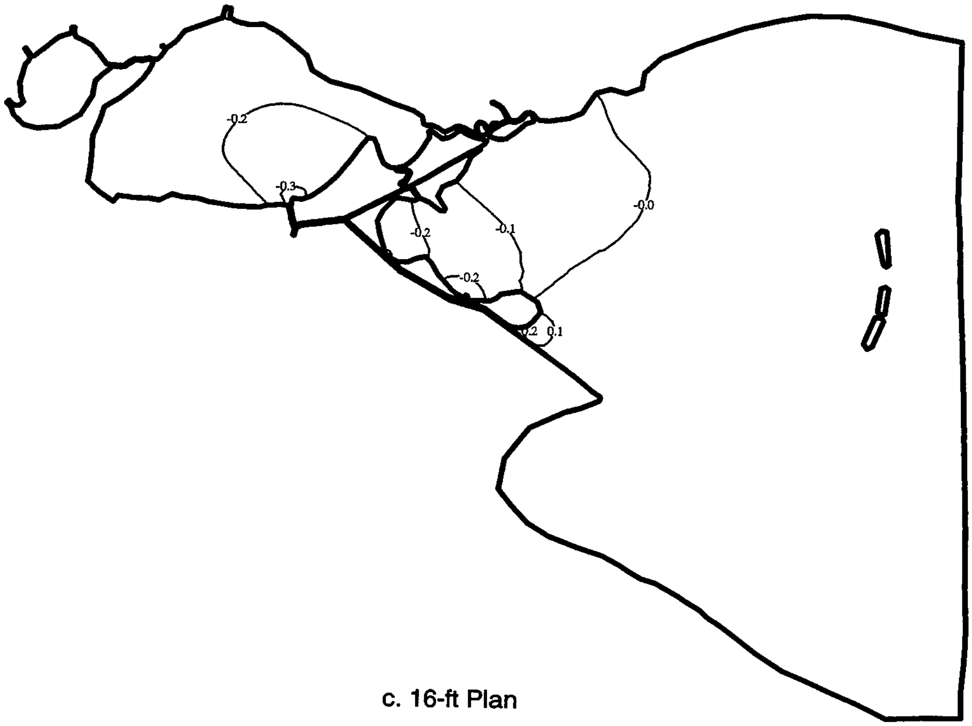


b. 20-ft Plan

Pontchartrain Basin Isohalines
Base and Plan Changes from Base
September



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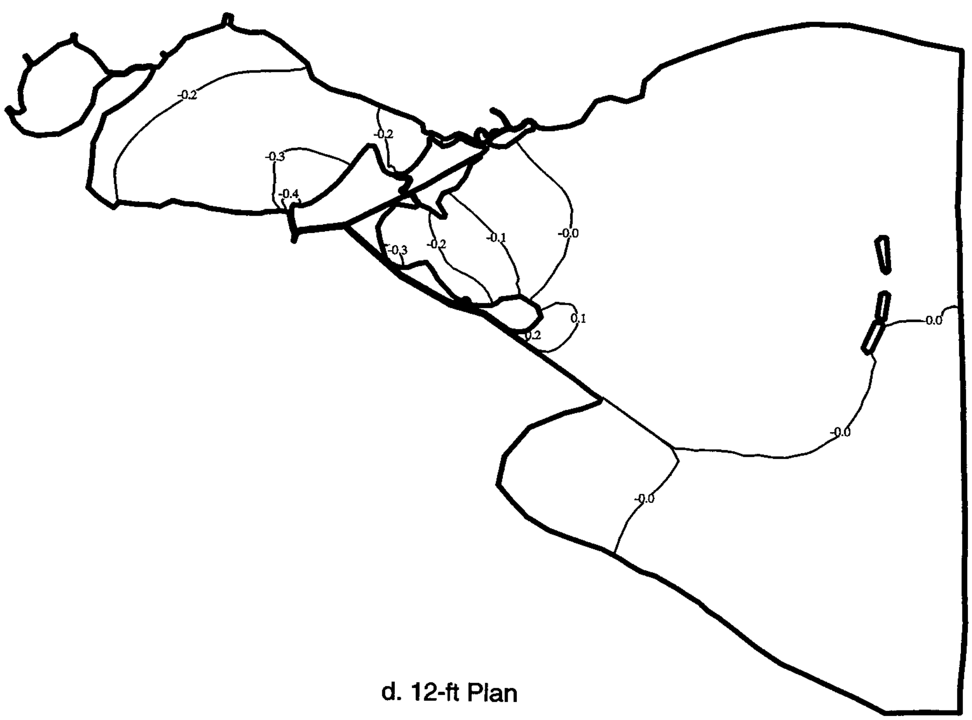
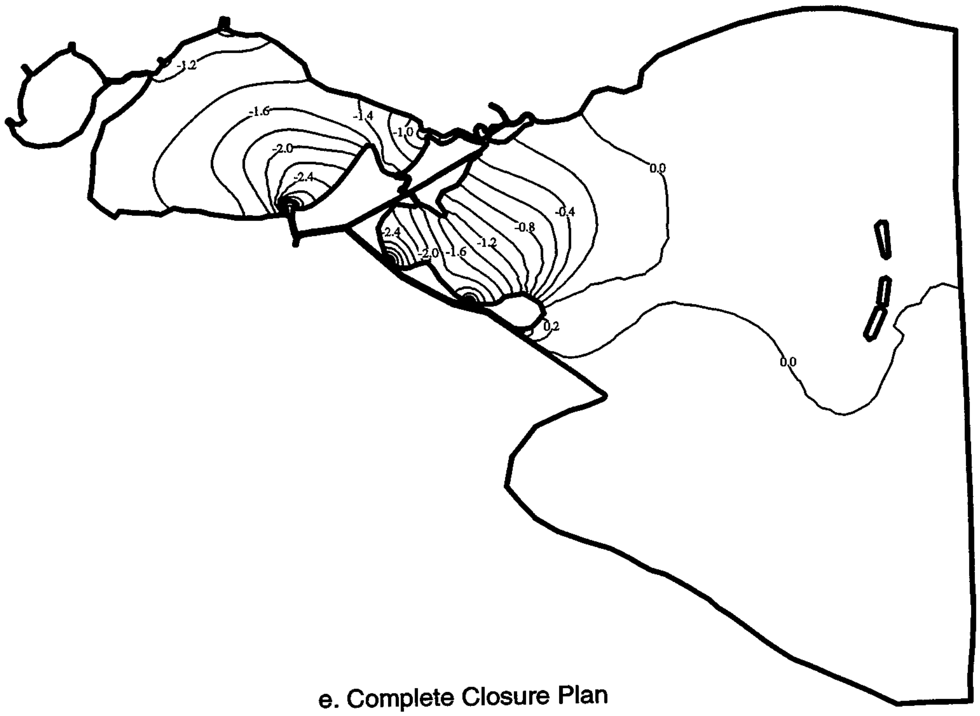


d. 12-ft Plan

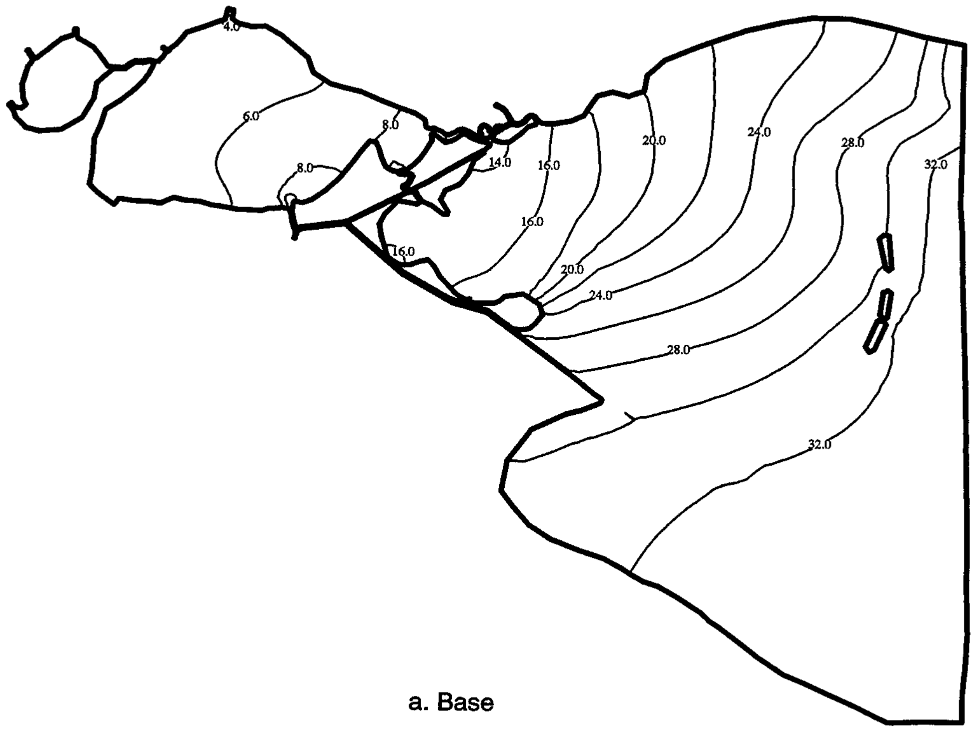
Pontchartrain Basin Isohalines
Base and Plan Changes from Base
September

Plate 3
(Sheet 2 of 3)



e. Complete Closure Plan

Pontchartrain Basin Isohalines
Base and Plan Changes from Base
September



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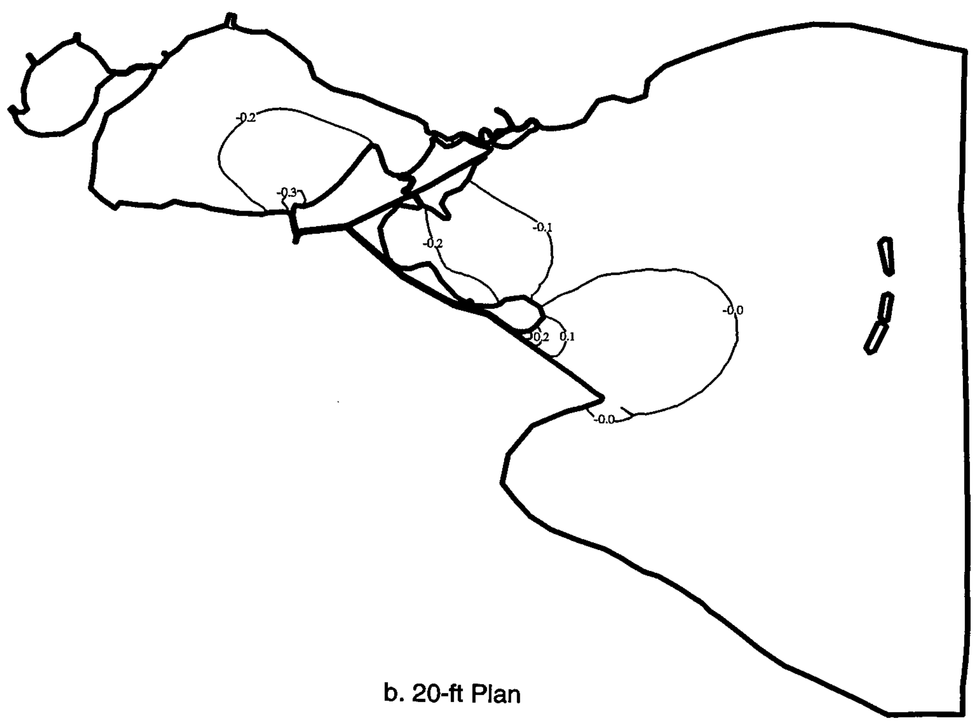
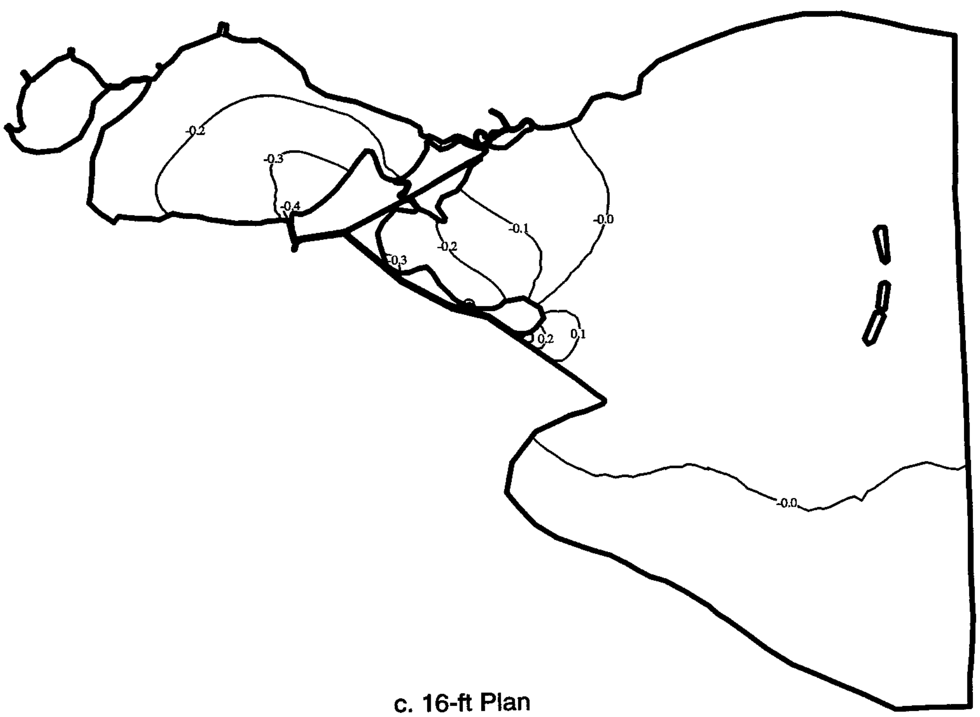


b. 20-ft Plan

Pontchartrain Basin Isohalines
Base and Plan Changes from Base
October

Plate 4
(Sheet 1 of 3)



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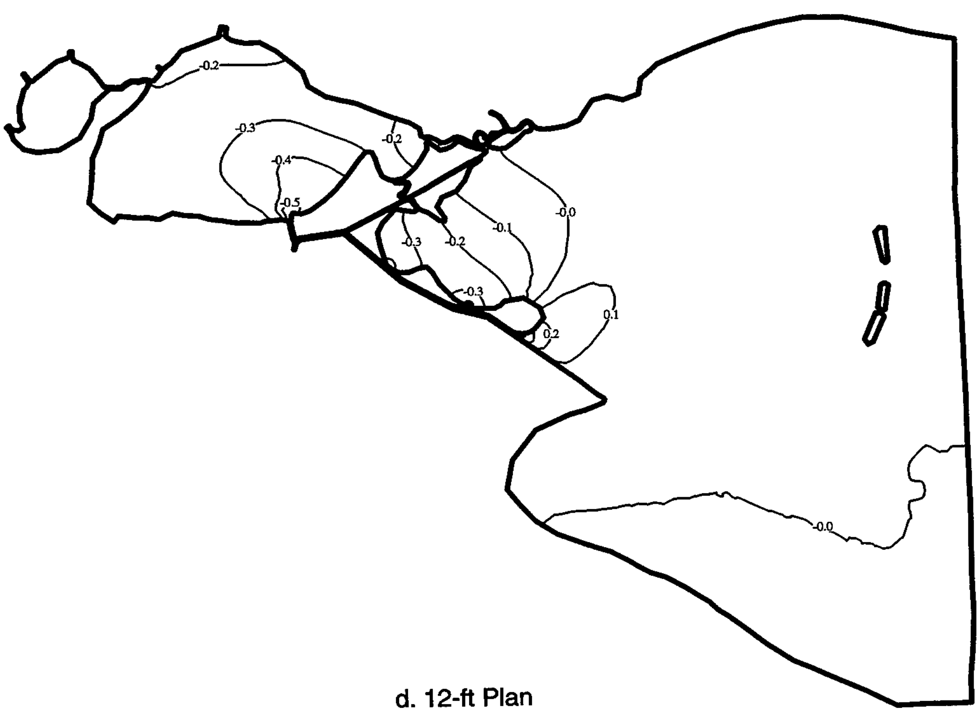
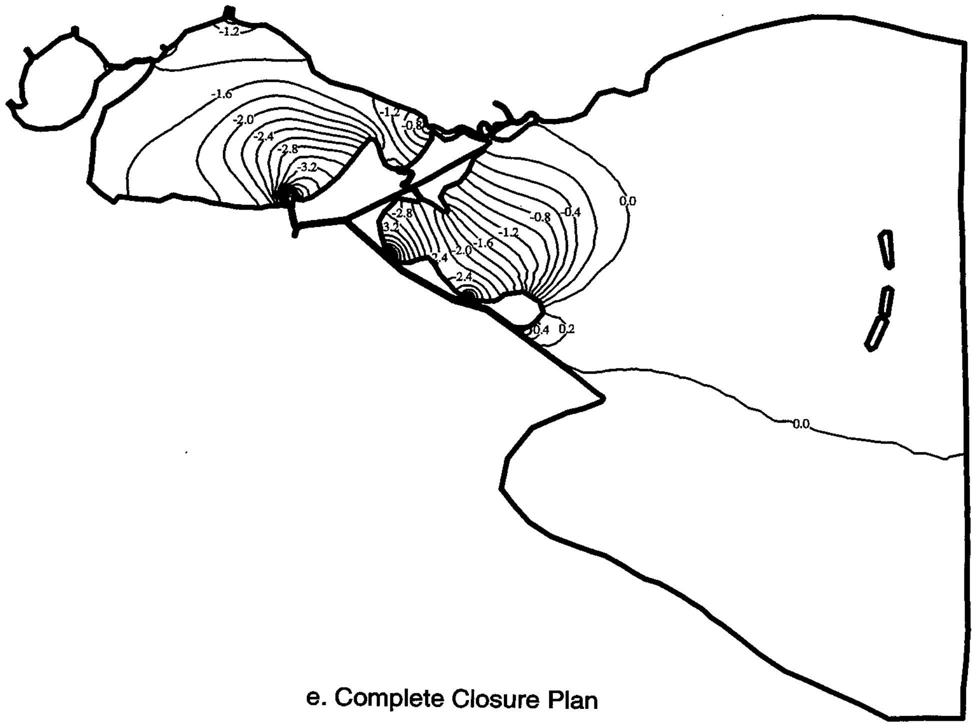


d. 12-ft Plan

Pontchartrain Basin Isohalines
Base and Plan Changes from Base
October



e. Complete Closure Plan

Pontchartrain Basin Isohalines
Base and Plan Changes from Base
October

Plate 4
(Sheet 3 of 3)

Appendix A The Hydrodynamic Code

The complexity of this estuary requires a numerical model that relies upon an unstructured computational mesh. The code chosen is the Galerkin-based finite element model TABS-MDS, which is a U.S. Army Engineer Research and Development Center (ERDC) adaptation of the RMA-10 code developed by King (1993).[1] This code computes time-varying open- channel flow and salinity/temperature transport in 1, 2, and 3 dimensions. It invokes the hydrostatic pressure and mild slope assumption. Vertical turbulence is supplied using a Mellor-Yamada Level II (Mellor and Yamada 1982) k-ℓ approach modified for stratification by the method of Henderson-Sellers (1984). The salinity/density relationship is based upon Pritchard (1982).

The full three-dimensional equations are reduced to a set of two momentum equations, an integrated continuity equation, a convection-diffusion equation, and an equation of state. The simplification is a result of the hydrostatic pressure approximation.

$$\rho \frac{Du}{Dt} - \nabla \cdot \sigma_x + \frac{\partial P}{\partial x} - \Gamma_x = 0 \quad \text{(A1)}$$

$$\rho \frac{Dv}{Dt} - \nabla \cdot \sigma_y + \frac{\partial P}{\partial y} - \Gamma_y = 0 \quad \text{(A2)}$$

$$\frac{\partial h}{\partial t} + u_\zeta \frac{\partial \zeta}{\partial x} - u_a \frac{\partial a}{\partial x} + v_\zeta \frac{\partial \zeta}{\partial y} - v_a \frac{\partial a}{\partial y} + \int_a^\zeta \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) dz = 0 \quad \text{(A3)}$$

$$\frac{Ds}{Dt} - \frac{\partial}{\partial x}\left(D_x \frac{\partial s}{\partial x} \right) - \frac{\partial}{\partial y}\left(D_y \frac{\partial s}{\partial y} \right) - \frac{\partial}{\partial z}\left(D_z \frac{\partial s}{\partial z} \right) = 0 \quad \text{(A4)}$$

$$\rho = F(s) \quad \text{(A5)}$$

[1] All references cited in this appendix are listed in the References section at the end of the main text.

Elevation-related terms are defined in Figure A1.

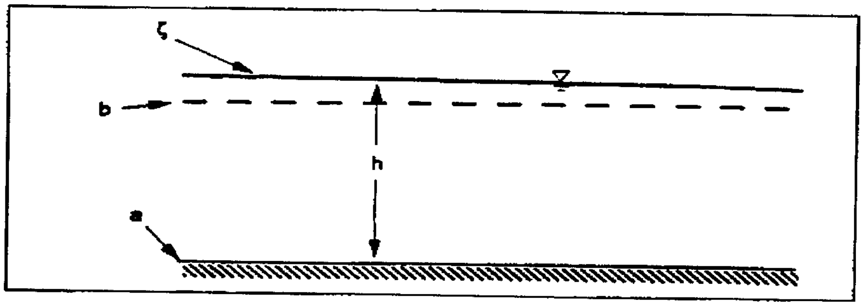


Figure A1. Definitions for elevation terms

where

$$\sigma_x = \left\{ \begin{array}{l} E_{xx} \dfrac{\partial u}{\partial x} \\ E_{xy} \dfrac{\partial u}{\partial y} \\ E_{xz} \dfrac{\partial u}{\partial z} \end{array} \right\} \; ; \; \sigma_y = \left\{ \begin{array}{l} E_{yx} \dfrac{\partial v}{\partial x} \\ E_{yy} \dfrac{\partial v}{\partial y} \\ E_{yz} \dfrac{\partial v}{\partial z} \end{array} \right\}$$

and

ρ = density

u,v,w = x,y,z velocity components

t = time

P = pressure

$$\Gamma_x = \rho\Omega v - \frac{\rho g\, u_a (u_a^2 + v_a^2)^{(1/2)}}{C^2} + \psi\, W^2 \cos(\Theta)$$

$$\Gamma_y = -\rho\Omega u - \frac{\rho g\, v_a (u_a^2 + v_a^2)^{(1/2)}}{C^2} + \psi\, W^2 \sin(\Theta)$$

Ω = $2\omega\sin(\varphi)$

ω = rate of angular rotation of the earth

φ = local latitude

g = gravitational acceleration

C = Chezy or Manning friction formulation

ψ = a coefficient from Wu (1980)

W = wind speed

Θ = wind direction counterclockwise from easterly

h = depth

u_ζ, v_ζ = x,y velocity components at the water surface

ζ = water surface elevation

u_a, v_a = x,y velocity at the bed

a = bed elevation

s = salinity

D_x, D_y, D_z = diffusion coefficient for salt

E = eddy viscosity components

The continuity equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{A6}$$

is solved as a second part of each solution step. Equation A6 is converted to an appropriate boundary value problem through differentiation with respect to z. After rearrangement it takes the form

$$\frac{\partial^2 w}{\partial z^2}=-\frac{\partial}{\partial z}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right) \tag{A7}$$

subject to boundary conditions specified for the water surface and the bed.

$$w_\zeta = u_\zeta \frac{\partial \zeta}{\partial x}+v_\zeta \frac{\partial \zeta}{\partial y}+\frac{\partial h}{\partial t} \quad \text{at the water suface} \tag{A8}$$

and

$$w_a = u_a \frac{\partial a}{\partial x} + v_a \frac{\partial a}{\partial y} \quad \text{at the bed} \tag{A9}$$

Note that in these equations the values of u and v will be known at all locations from the previous part of the solution step. Values of w in this solution are used in the next iteration for u,v,h, and s.

The geometric system varies with time; i.e., the water depth h varies during the simulation. In order to develop an Eulerian form for the solution, it is desirable to transform this system to one that can be described with a constant geometric structure. Early development of the model (King 1982) used a σ-transformation in which the bed and the water surface are transformed to constants. In a later analysis of this method, King (1985) pointed out that at locations where a sharp break in bottom profile occurs, the transformation is not unique and momentum in the component directions may not be correctly preserved. An alternative transformation that preserves the bottom profile as defined, but transforms the water surface to a constant elevation is now used (z^∇ transformation).

This transformation is defined by:

$$x^\nabla = x \tag{A10}$$

$$y^\nabla = y \tag{A11}$$

$$z^\nabla = a + (z - a)\frac{(b - a)}{h} \tag{A12}$$

where b is the fixed vertical location to which the water surface will be transformed. Equations A1-A6 and A7-A9 then incorporate the transformation (A10-A12).

Another advantage of this transformation is that it produces z^∇ = constant lines that are close to horizontal, i.e., z = constant lines. This results in less fictitious density-driven currents near bed profile breaks (Stelling and van Kester 1993). Since stratification-related phenomena are usually nearly horizontal, it is important that the transformation leave constant surfaces that are nearly horizontal. Considering the pressure gradient (due to the density gradient) in this transformation produces

$$\frac{\partial P}{\partial x} = \frac{\partial P}{\partial x^\nabla} + \frac{\partial P}{\partial z^\nabla}\frac{\partial z^\nabla}{\partial x} \tag{A13}$$

In a strongly stratified stagnant system this pressure gradient should be zero. However, note that Equation A13 in the transformed system is dependent upon two terms (each of which could be large) to cancel each other. This could cause artificial currents due to truncation and roundoff error. A transformation in which $\partial z^{\nabla} / \partial x \approx 0$, i.e., $z^{\nabla} \approx z$, will reduce this problem. Figure A2 shows an example for a case in which a 40-ft-deep channel passes through an 8-ft-deep bay. Here b is chosen to be an elevation of 0 and ζ is 2 ft. Near the break in the bed profile $\partial z^{\nabla} / \partial x$ is fairly small, or z^{∇} surfaces are nearly horizontal. Contrast this with the σ transformation in Figure A3. The σ = constant surfaces are far from horizontal along the channel side slopes. The truncation and round-off errors tend to drive fictitious currents that cause the denser salt water to leave the channel. The z^{∇} transformation results in

$$\frac{\partial z^{\nabla}}{\partial x} = 0(\zeta - b) \tag{A14}$$

whereas the σ transformation is

$$\frac{\partial \sigma}{\partial x} = 0(h) \tag{A15}$$

is much larger.

The Galerkin finite element approximation of Equations A1-A4 and A7 uses a quadratic approximation for u,v,w, and s and linear for h and P. The nonlinearity is addressed by Newton-Raphson iteration at each time-step. Generally the iteration process is split into calculation of Equations A1-A3, then A7, followed by A4. This sequence is repeated until sufficient convergence is reached.

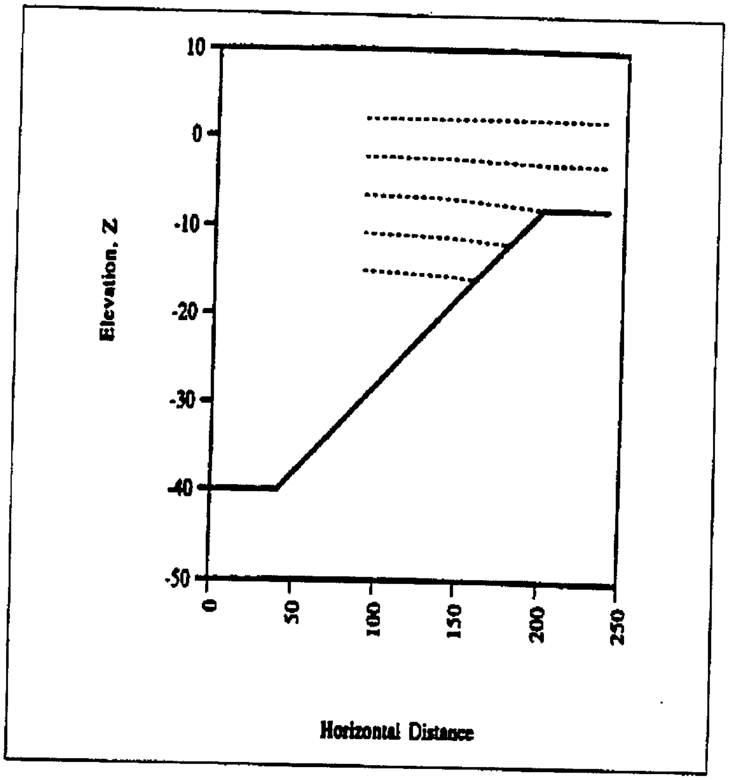


Figure A2. Lines of constant $\bar{z}^{\nabla}$ near a significant grade change

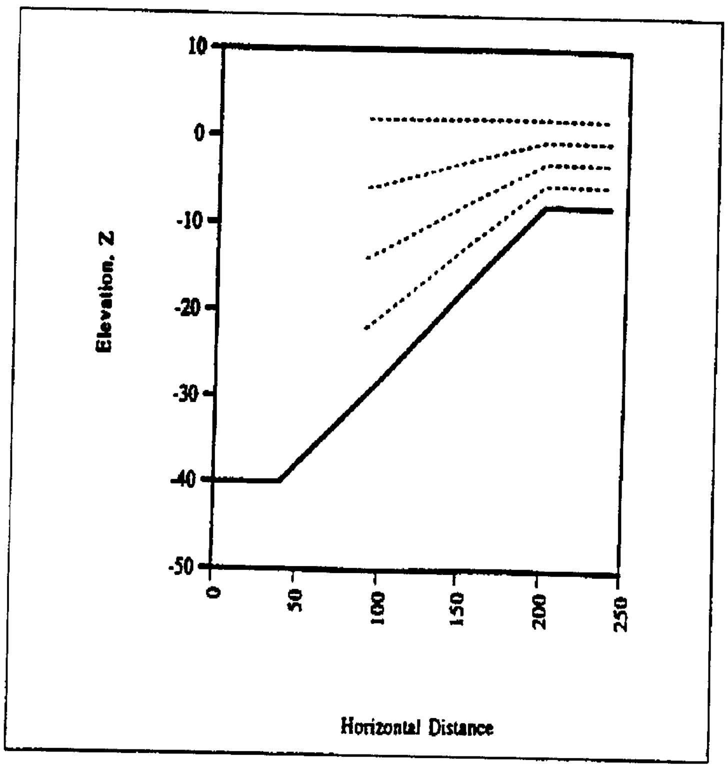


Figure A3. Lines of constant σ near a significant grade change

Appendix B Hurricane Juan

Introduction

Based on the results of the initial study, additional inquiry was requested to evaluate the length of time necessary for the system's salinity to return to normal observed levels after an unusual weather event. In this case, the surge from Hurricane Juan is used to constitute this event.

To accomplish this goal, the two situations previously modeled, open Mississippi River Gulf Outlet (MRGO) and closed MRGO, are investigated again under extreme conditions by applying hurricane surge superimposed on the normal astronomical tide to the easternmost boundary of the model, in the vicinity of Biloxi.

Methodology

The tidal record for the NOAA station Cadet Point in Biloxi Bay, MS, was evaluated to pinpoint the passing of extreme conditions over the area, such as a hurricane. Hurricane Juan made landfall on October 27, 1985, and was used for this analysis. The observed tidal data for October 1985 were then compared to the predicted tide for the same period. The predicted astronomical water surface elevations for October 1985 were generated. Figure B1 shows both the predicted and observed water surface elevation for October 1985.

The difference between the two data sets was then added to the June astronomical tide used in the prior modeling efforts. The resulting tidal record was then applied at the Biloxi boundary to run the model (See Figure B2).

Five locations were chosen for salinity analysis: the middle of Lake Borgne, Marcello Castle, Chef Pass, Little Woods, and in the middle of Lake Pontchartrain. For each of these locations, the difference between normal conditions and the hurricane event was computed under both situations: open MRGO and closed MRGO. That is, the salinity for normal conditions was subtracted from the salinity found under hurricane conditions. So a positive salinity means that the hurricane raised the salinity at that point. This was done for MRGO open and also with MRGO closed and are shown in Figures B3-B7.

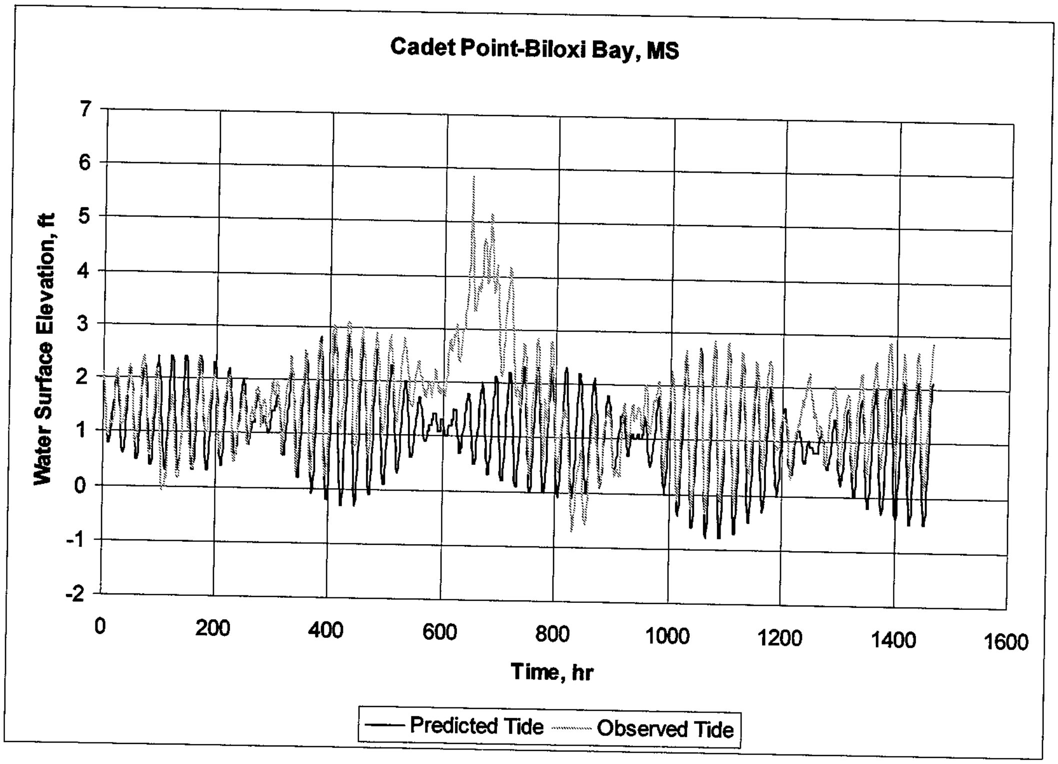


Figure B1. Predicted and observed water surface elevation at Cadet Point, Biloxi Bay, MS during October and November 1985

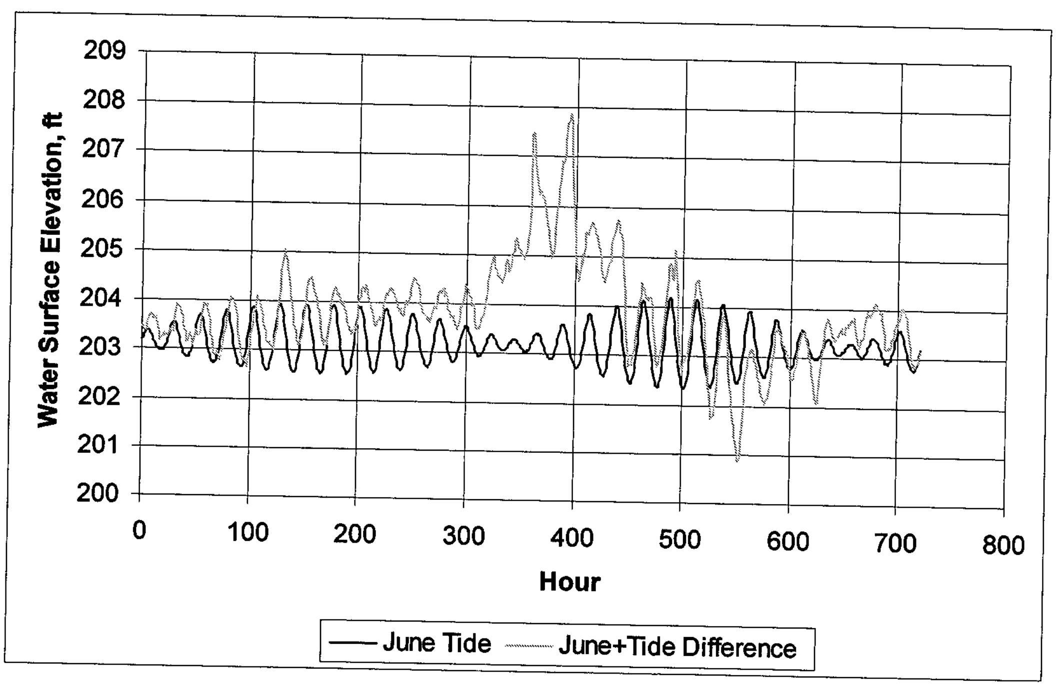


Figure B2. Observed June tidal record and computed tidal record resulting from addition of hurricane event

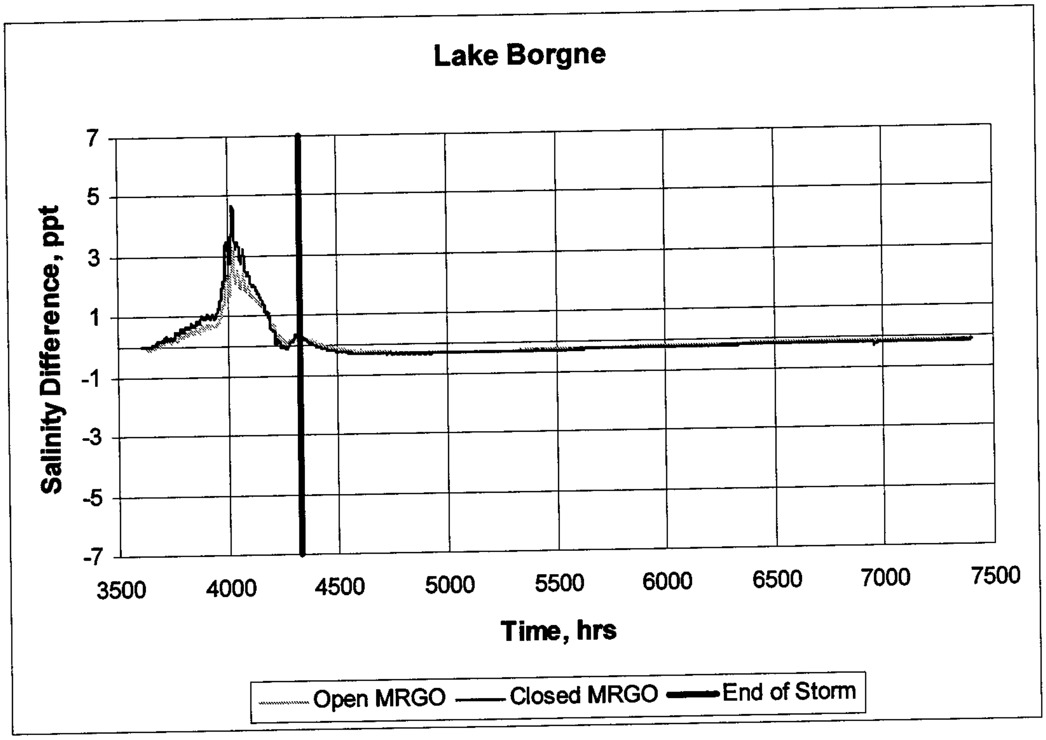


Figure B3. Difference in salinity between normal and hurricane conditions at Lake Borgne with MRGO open and closed

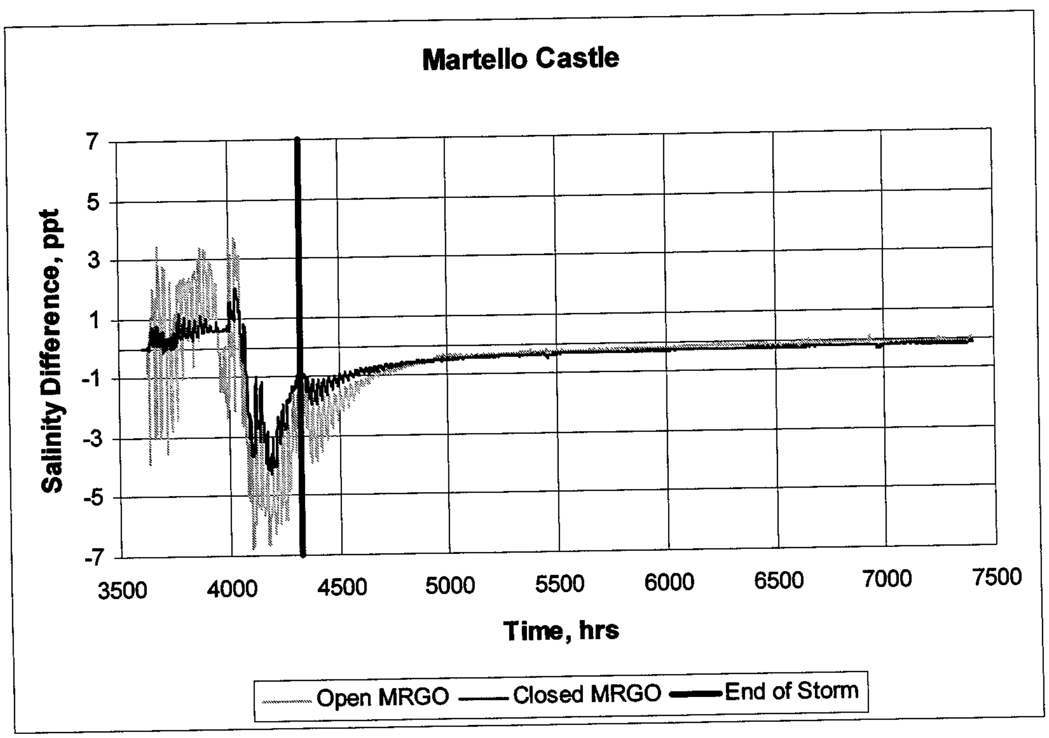


Figure B4. Difference in salinity between normal and hurricane conditions at Martello Castle with MRGO open and closed

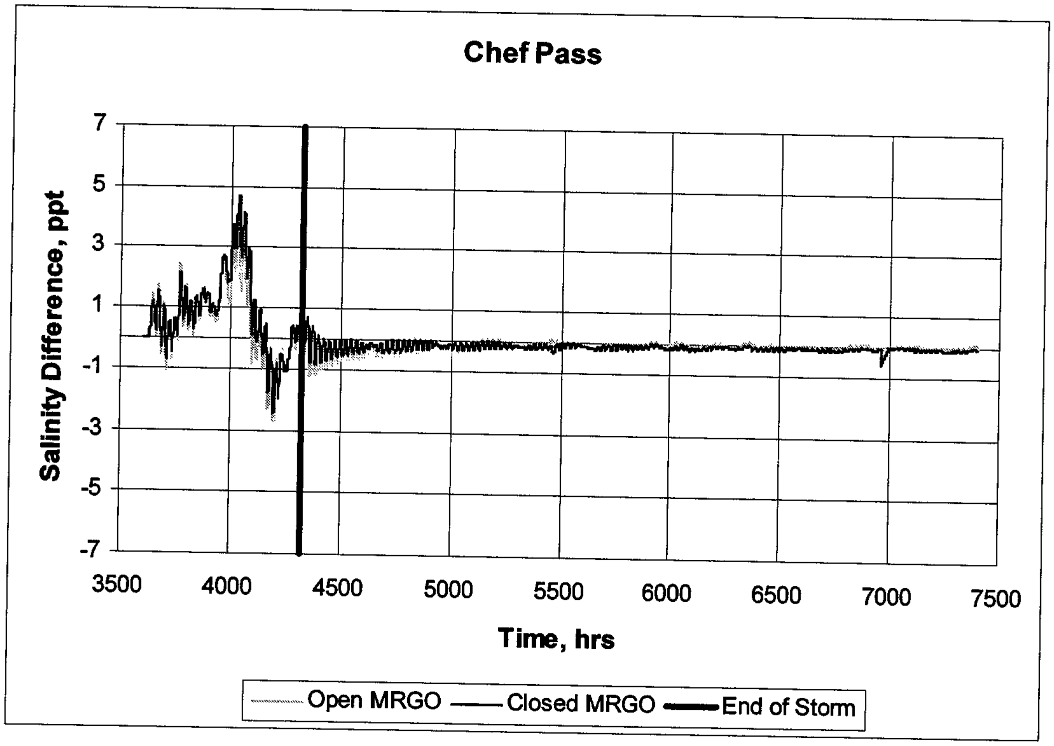


Figure B5. Difference in salinity between normal and hurricane conditions at Chef Pass with MRGO open and closed

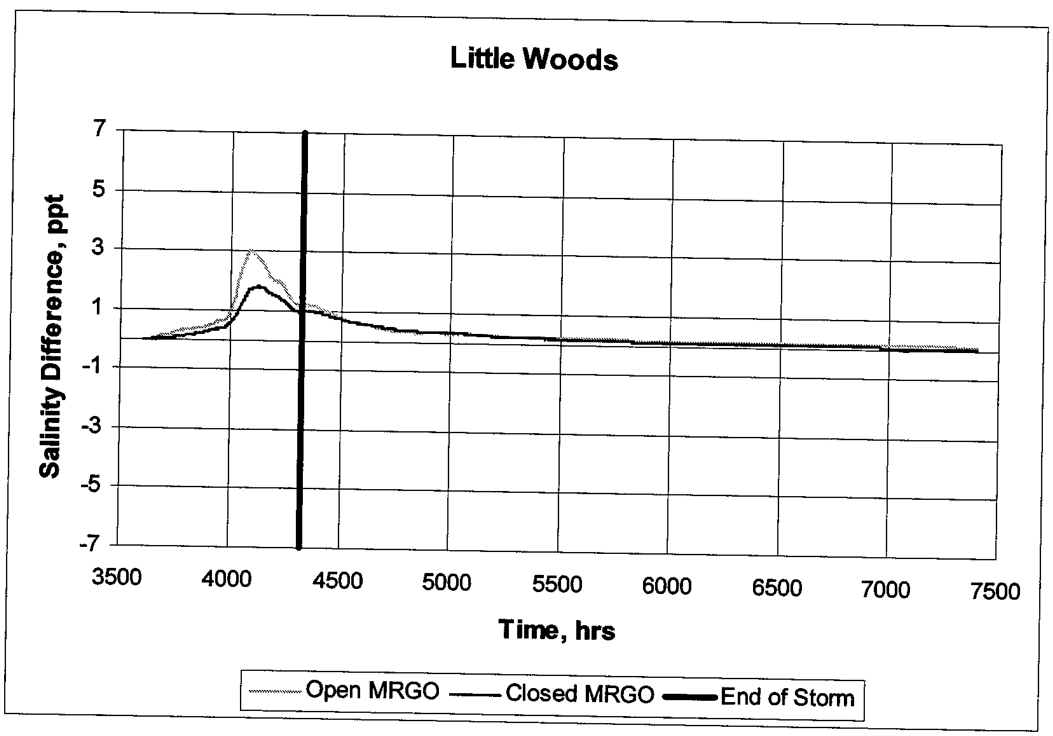


Figure B6. Difference in salinity between normal and hurricane conditions at Little Woods with MRGO open and closed

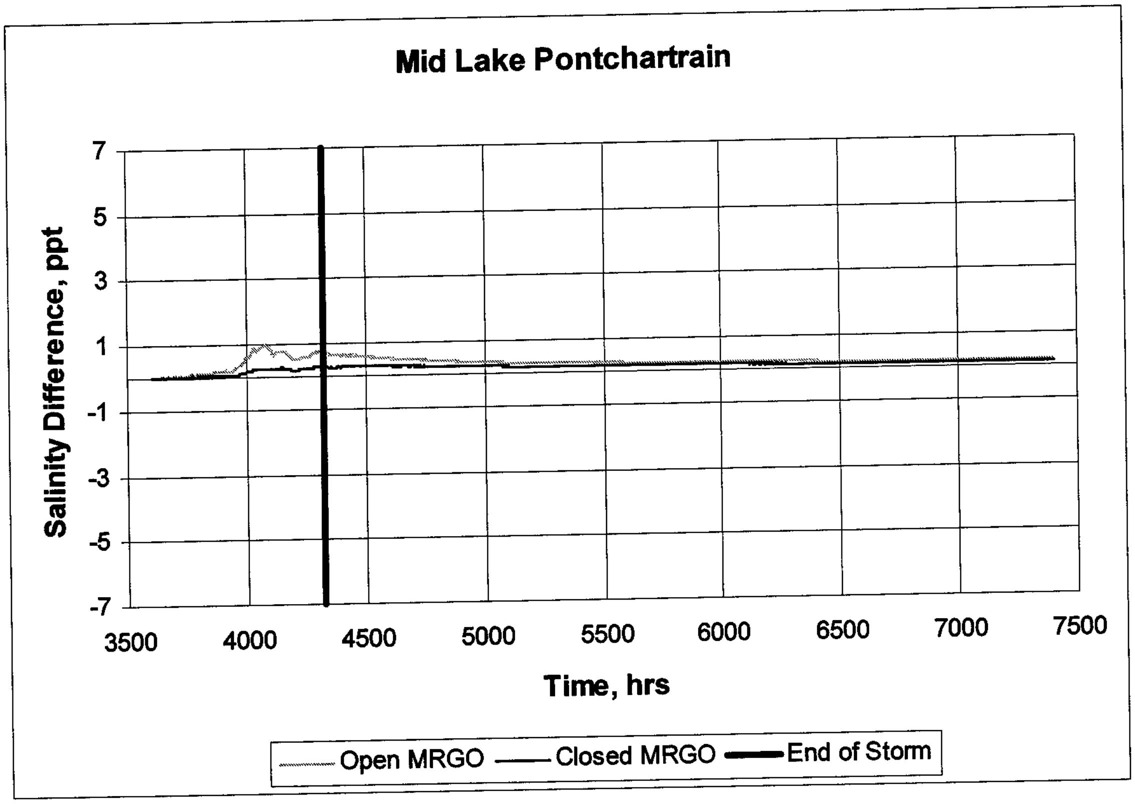


Figure B7. Difference in salinity between normal and hurricane conditions at mid Lake Pontchartrain with MRGO open and closed

Discussion

The figures illustrate that the area near the MRGO channel are more affected by the hurricane. Another observation is that there is generally some slight residual of the hurricane remaining after over 3,000 hr. So the system has a very long residence time. The difference between MRGO open and closed seems to shrink rapidly, so that the recovery time for each seems to be about the same.

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14. ABSTRACT

The Mississippi River-Gulf Outlet (MRGO) consists of a ship channel 36 ft deep and 500 ft wide, extending approximately 76 miles from the junction of the Inner Harbor Navigation Canal and the Gulf Intracoastal Waterway in New Orleans, LA, to the -38 mlw (mean low water)-ft contour in the Gulf of Mexico. The purpose of the MRGO is to provide a deep draft channel to the Port of New Orleans Inner Harbor facilities. Since the MRGO's completion in January 1968, saltwater flux from the MRGO through direct connections to Lake Borgne and the Gulf Intracoastal Waterway has contributed to an increase in the salinity concentration of the lakes and Biloxi Marshes. This report presents the results of a numerical model investigation used to predict average salinity changes that will occur in the Lake Pontchartrain Basin as a result of varying levels of closure of the Mississippi River-Gulf Outlet below Lake Borgne.

15. SUBJECT TERMS

Mississippi River	Gulf outlet
Gulf Intracoastal Waterway	MRGO

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